The Ongreening Pavilion

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Abstract. *This paper describes the work of Ramboll Computational Design during the design and construction of the Ongreening Pavilion timber gridshell. The structural approach involved form-finding bending-active timber laths, connected at intersections to form a doubly curved shell. The resulting form was simple to fabricate and assemble, realised using 6.5mm thick Finnish birch plywood laths that could achieve high curvature while maintaining desired strength. Due to the random nature of the final lath topology, the resulting structure was extremely stiff in spite of its low material weight, acting similarly to a continuous monocoque. The fully demountable shell was first erected at Ecobuild 2014 in London.*

1 Introduction

In late 2013, Ramboll Computational Design (RCD) were approached by Ongreening Ltd to assist with the design of a temporary pavilion to mark the launch of their new web-based platform for green building. The pavilion structure was required to be demountable, made from timber and fit within a given 10m x 8m plot secured at Ecobuild 2014 in London, a public exhibition on sustainable building.

During the initial design phase, Ongreening Ltd expressed an early desire for a single-layer gridshell formed from pre-stressed timber members of constant bending stiffness that form so-called elastica curves [Levien 2008]. Although typical structures attempt to avoid bending behaviour, bending-active structures instead utilise bending to give rise to form in a pre-buckled state.

Traditional pre-stressed timber gridshells have a lattice with a fixed topology which is first laid out flat and then pushed into shape. The form is manipulated by allowing an in-plane rotation at each connection which is then fixed when the desired shape is found [Harris et al. 2004]. Such methods have successfully been used on The Mannheim Multihalle [Burkhardt et al. 1976], The Downland Gridshell [Harris et al. 2003] and The Savill Building [Harris et al. 2008].

For the Ongreening Pavilion, due to the size restrictions of the site it became clear early on that a similar method would not be possible, and also restrict the solution space during design exploration whilst attempting to meet client requirements.

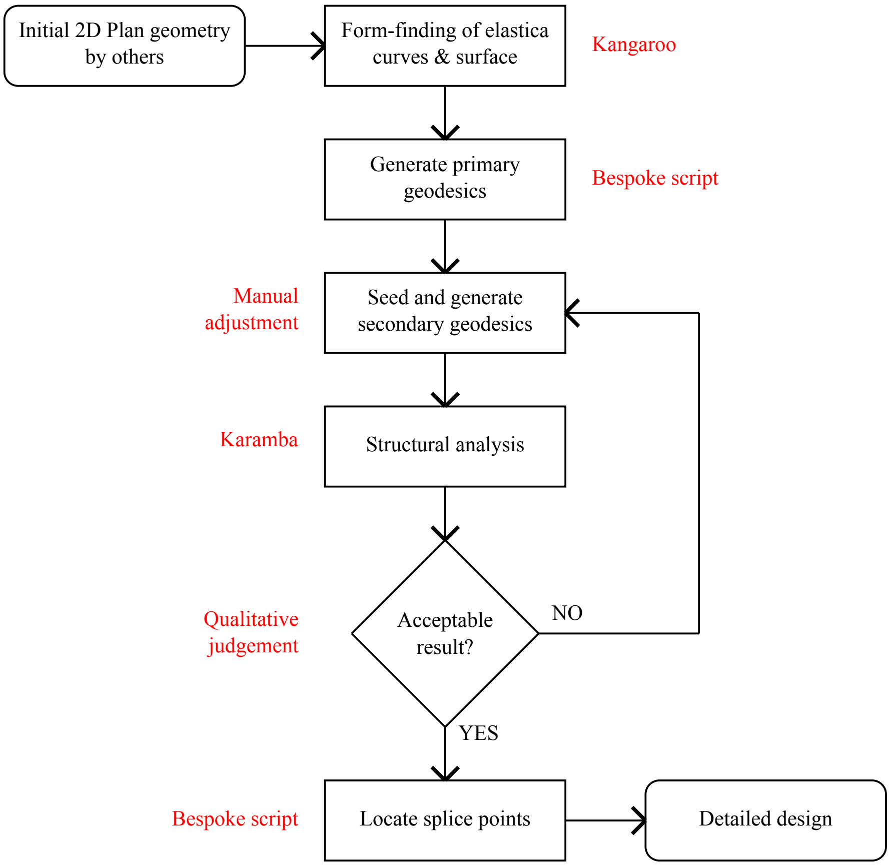

Figure 1: Schematic diagram showing overall process in generating the final geometry

Instead, a method of bending each individual lath *sequentially* was adopted. This meant that a wider variety of forms could be explored but at the cost of requiring a more complex assembly. Due to the small size of the pavilion, this compromise was deemed to be acceptable. The final approach adopted was similar to that used on The Faraday Pavilion [Nicholas et al. 2013], the Smartgeometry 2012 gridshell [Kudless 2012] and recent developments in using bending-active elements for tension structures [Van Mele et al. 2013] whereby the grid topology is not pre-prescribed, but rather emerges as part of a simulation.

Bending active gridshells often have a rotationally symmetry cross-section, so that any torsion in the member does not effect the orientation of the connection details at member intersections. For example, the Faraday Pavilion was constructed using fibre reinforced polymer tubes. For The Ongreeening Pavilion however, flat timber laths were proposed with a particular grain direction, thus adding an additional design constraint.

The overall process of generating the geometry is shown in Fig. 1. This first involved the form-finding of planar curves that defined a freeform surface. This surface was then used to derive a set of primary laths based on geodesic lines. Secondary elements were then woven around these primaries, again by generating geodesics this time from a more random set of seed points that were refined manually. Finally, splice points along the laths were located, with the final geometry then exported for detailed design.

2 Initial Form-finding

In theory, any doubly curved shape can be discretised into flat, straight laths so long as their paths follow surface geodesics [Pirazzi et al. 2006]. However, during the process of construction it is advantageous for each lath to take its required shape using a minimal amount of effort. For example, by pushing the ends of a single lath with constant material properties and allowing it to deform a particular curved geometry is found for each single lath which can then be used to set out the shell. It was therefore decided to derive a set of *primary* laths that during the first-phase of assembly would take up a particular bending-active shape when constrained at their ends.

To simplify the process, these primary laths were initially assumed to be planar, vertically oriented and set out radially on plan. The setting out was based on a plan drawing by Ongreening Ltd with a central circular focus point and an elliptical boundary. A continuous shell was generated by lofting through these curves. The process (see Fig. 2) is described as follows:

1. Place node points on an inner circle
2. Create radial lines from each node point
3. Trim radial lines with outer ellipse and apply bending stiffness to the element
4. Increase natural length of elements and solve using dynamic relaxation

5. Constrain curves to a vertical plane by applying a small gravitational field
6. Adjust natural length of elements according to a trigonometric function

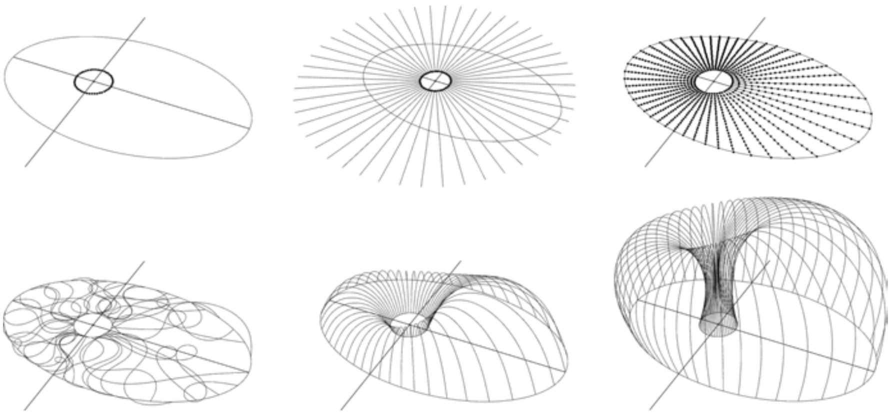

Figure 2: Form-finding process for bending active shell

2.1 Dynamic Relaxation

Numerical form-finding techniques for large displacements were required to understand the equilibrium of bending-active shapes. A simple dynamic relaxation process using Euler integration was carried out using within Grasshopper with the Kangaroo physics plug-in [Piker 2013].

Following the initial form-finding it was found that with pinned connections the laths were clashing at the central area. This was resolved by replacing the inner pinned connections with fixed ones, constraining each lath at its end to a vertical direction and giving rise to a regular funnel structure at the centre of the pavilion. A total of 32 primary elements was found to give the required visual density for the pavilion whilst avoiding overlapping laths at the funnel (see Fig. 3).

2.2 Geodesic Replacement

A reference surface for the shell was created by performing a closed loft through the 32 primary curves. The original intention was that these curves would form the primary structural elements however due to the nature of the final surface when these curves were unrolled they were not straight and therefore harder to fabricate from standard timber sheets. In contrast, geodesic lines between two points on a continuous, doubly curved surface form straight lines when unrolled to a plane, making them very efficient for 3-axis CNC fabrication.

The original radial curves used to form the surface were therefore replaced by geodesics by seeding from the same points on the inner circle that were used to

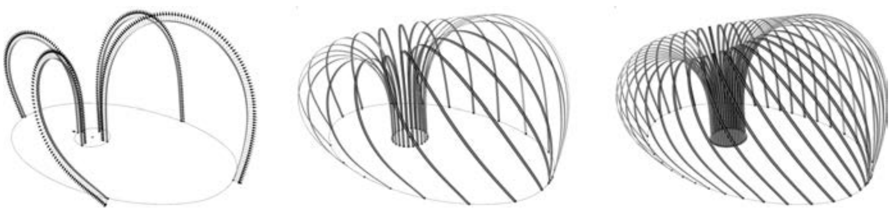

Figure 3: Orientation of the primary laths showing the final density

create the radial lines. These new curves were not restricted to the vertical plane and therefore introduced some torsion into the laths. It was assumed, however, that these resultant geodesics would still closely approximate the shape of a bent lath when supported at each end, assuming self-weight was negligible when compared to the pre-stress.

As well as generating a geodesic line between two given points on a surface, a geodesic or *plank line* may also be generated using an iterative approach [Kensek et al. 2002]. By using a seed point, initial direction and step size, a new point is generated that is then projected back to the surface. This point becomes the next seed, with a new direction vector found by combining the previous direction with the current surface normal.

For the pavilion, this process continued until the projected point lay on the surface boundary. A smooth curve was then created by interpolating between the set of points. As with any integration approach, a relatively small step-size was required to produce an accurate result.

Each of the 32 primary laths were realised in 6.5mm thick Finnish birch plywood and 100mm wide. A second layer of laths interconnecting the primaries, was required to make the structure stable and act as a gridshell.

3 Placing of Secondary Laths

As previously mentioned, it is commonplace for gridshell structures to have a rectangular or diagrid topology. However, for the Ongreening Pavilion a more random aesthetic of laths was desired by the client, giving a woven-like appearance. Secondary laths were therefore wrapped around the primary elements again along geodesics in order to give the shell strength in all directions (see Fig. 4). This had the added benefit of making the shell membrane less directionally oriented (as with a diagrid) and therefore act more like a continuous shell or monocoque structure such as an egg shell.

Extending the method used for the primary elements, a number of secondary laths were created using a random distribution of seed-points and starting vectors. The secondary geodesics were generated in both directions from the their seed points, terminating at the shell boundary. As per the primary laths, the secondaries were realised again from 6.5mm thick birch plywood, this time 75mm wide.

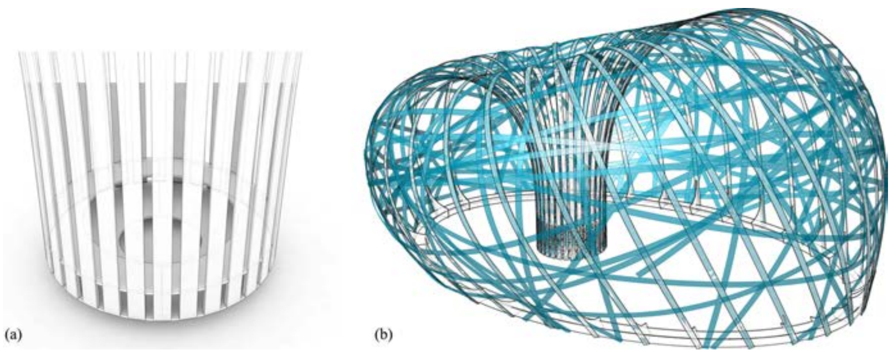

Figure 4: a) Central funnel detail. b) Wrapping the primary laths with secondary elements in the computer model

3.1 Real-time Structural Analysis

It was found that the initial random seeding of the laths led to significant bunching of the secondary geodesics. This was deemed unacceptable because: a) an even distribution of laths was required by the client on aesthetic grounds, b) it led to multiple laths weaving at nearby locations, thus negating the thinness of the shell, c) the structural performance was poor due to large gaps with no secondary structure. Manual adjustment to the seed points was adopted in order to create a desirable arrangement of secondary elements.

This process was therefore driven by aesthetic, fabrication and structural grounds. For the latter, feedback was given due to the structural analysis being directly linked to the parametric geometry using the Grasshopper plug-in Karamba [Preisinger 2013] (see Fig. 5). This real-time linear analysis was conducted within the parametric model itself, allowing the performance of each configuration to be understood immediately.

The Karamba plug-in provided fast finite element analysis, perfectly suited for the conceptual design stage of small-scale, complex structures. Load combinations could be tested on the fly, along with redundancy checks, to better understand an appropriate density of secondary members for the shell. The ability to immediately interrogate a structure after each and every modification to the design was very useful when paired with the ability to interpret the results and make intelligent design decisions. Instead of finding an *optimal* result and excluding the human user, real-time analysis was used *in combination* with human intuition and qualitative judgement throughout the design process.

Once the secondary elements were finalised, the model was exported to Sofistik for further non-linear analysis and verification, which was found to give almost identical results. Both analysis models were set up to include self-weight and several imposed loads as prescribed by Ecobuild. The utilisation of each lath according to Eurocode 5 was determined using the sum of both the stresses due to loading and the

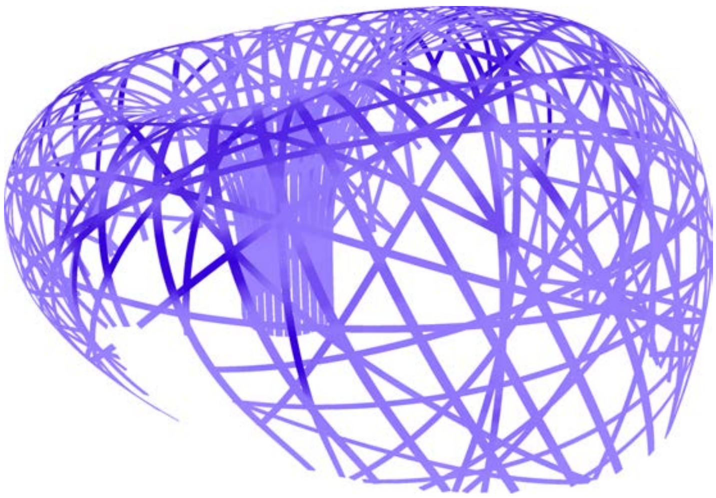

Figure 5: Real-time structural analysis within the parametric model. Darker shades show larger deflections

stress induced by bending the lath to the required curvature. It was found that 6.5mm thick Finnish Birch plywood was the best combination of high bending capability and high strength.

4 Details and Fabrication

The final topological layout of the timber laths is shown in Fig. 6. A numerical reference system was used for ease of assembly, with the pavilion being assembled as a kit of parts on site, with each primary element indicating which seondary was connected. These were simply pencilled onto the lath manually to avoid compromising the timber with engravings.

Although the random lacing of secondaries is visually interesting, when compared to the adoption of a diagrid there were several additional complexities that had to be addressed:

- The order of the overlapping laths is complex.
- Splice points have to be carefully set out so as not to clash with connections.
- A random topology means random connection locations along each lath.

4.1 Connections

With the lath geometry fixed, a second parametric model was developed to produce fabrication information. With the laths represented by centreline curves, points of intersection could be easily identified. Pinned connections were to be made at each

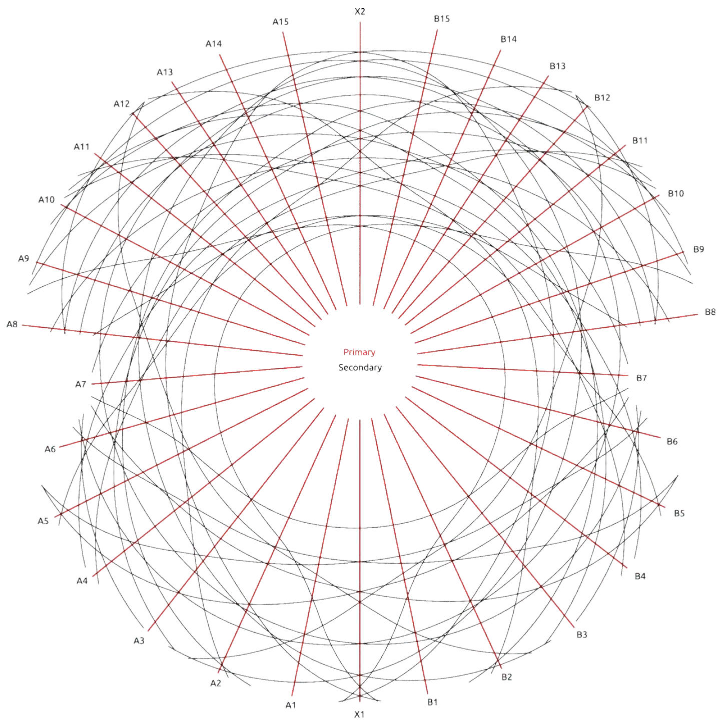

Figure 6: Disk projection showing the topology of the radial primary elements (red) and secondary elements (black).

intersection between primary and secondary laths. These could be stored as curve parameters to allow the drilling locations to be mapped to the unrolled laths. Intersections between secondary laths (including self-intersections) were also identified and used when locating splice points.

The timber laths themselves were made up of multiple elements with temporary splice locations, thus making the structure demountable and able to be fabricated from standard sized plywood sheets. These splice locations were generated within the same parametric model as the connections. The length of each individual element was maximised, taking into account fabrication constraints, whilst simultaneously avoiding locating splice points near connections or overlapping laths (see Fig. 7) . Secondary splice connections were slotted to allow for small adjustments during assembly and allow for the weaving of secondary laths over each other.

All connection and splice details (see Fig. 8) were designed to Eurocode 5, with physical testing of a single lath also conducted in order to verify the design when bent to tight radii, especially at the overlapping locations where stiffness is increased.

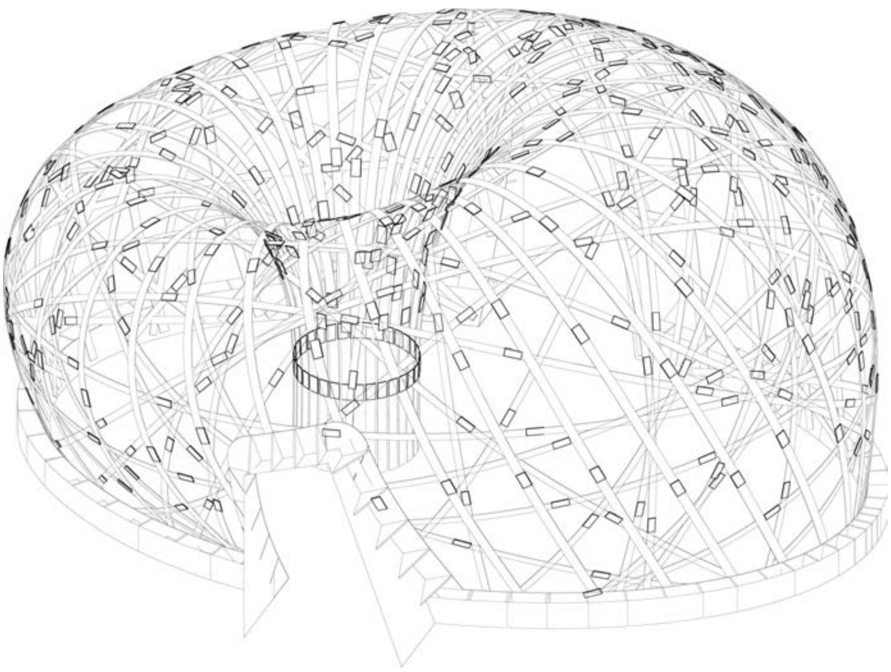

Figure 7: Optimal splice locations avoided intersections between laths whilst minimising their number

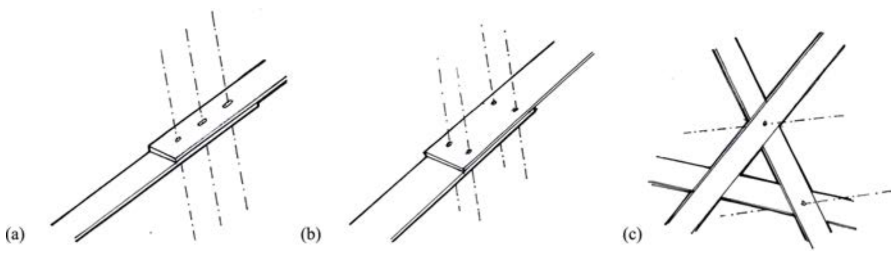

Figure 8: Simple M6 bolted connection details used on the pavilion: a) splice between two secondary elements with two slotted holes, b) splice connection between two primary elements, c) Primary to secondary connections

4.2 Fabrication

The use of birch plywood was absolutely essential to achieve the bending radii whilst still retaining the required shell strength at such a thin size. The fact the shell could be made from such thin plywood (6.5mm), also meant material use for this size of enclosure was minimised. Finishing materials were also made from birch plywood, for example the timber that wraps around the base of the structure.

The birch plywood used was FSC sourced and due to the pavilion being for internal use only, could be left with its original finish to express the timber. The use of timber also meant that the laths could be easily cut and connection holes drilled by a standard 3-axis CNC machine. Because of the geodesic geometry, when unrolled the laths were completely straight and therefore material wastage was almost zero when cutting the timber (see Fig. 9).

4.3 Perimeter Details

It was important to maintain a continuous boundary for attaching the primary and secondary laths and avoid free edges. Doorways were created along the line of the primary members at each side of the pavilion, with their edges a continuation of the base detail.

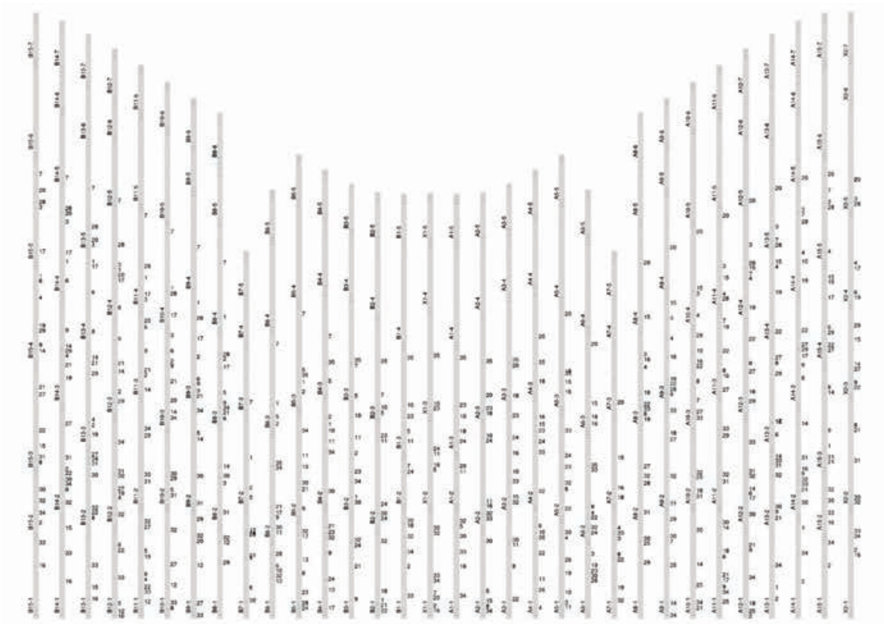

Figure 9: As all the elements followed geodesic lines on the surface, when unrolled they were straight and simple and efficient to manufacture.

5 Final Assembly

The gridshell took a small team three days to assemble, beginning with the perimeter and floor construction, moving onto the primary elements and then finally lacing with the secondaries.

The primary elements were prefabricated at their full length on the ground before bending and connecting to the perimeter. The secondary elements however were assembled in their actual position on the shell by wrapping around the primaries and connecting at splice points whilst moving around the structure.

Having real-time feedback from the analysis model again proved useful when determining the best sequence for constructing the pavilion. On their own each full length primary lath was unstable, relying heavily on the lateral support provided by the secondaries. Various combinations were explored until a secondary lath was identified that wrapped around the outside of the structure three times, at an approximate height of 2m and therefore reachable from ground level. Each individual length of this particular secondary lath could be added incrementally, connecting the primary laths to each other and providing the necessary lateral restraint. In reality, during construction additional secondaries were also able to be added to provide additional stability.

The slotted connections at the secondary splice points proved to be essential in terms of allowing some tolerance to weave the elements, especially in areas of high connectivity. On one or two occasions, additional holes were drilled where several elements overlapped on site, however due to the nature of working with timber this was easily resolved.

The final structure is shown in Fig. 10 and Fig. 11. As the structure was open to the public is was important that it worked as predicted by the analysis model and this was indeed the case, with the entire structure feeling very robust.

Figure 10: Internal view of realised pavilion at Ecobuild 2014

Figure 11: External view of realised pavilion at Ecobuild 2014

6 Conclusion

The project was instigated and financed by Ongreening Ltd to mark the launch of a new web based platform for sustainable building. In this sense, the value of the pavilion was important not just financially, but also in showing the potential of timber as a versatile material.

The pavilion shows what can be achieved with computational design techniques when using traditional low-cost and low-carbon materials such as timber and relatively simple fabrication techniques as a constraint. The final result points the way to similar thin shell structures with bending active elements that do not require additional processes such as steam bending.

During the design process, real-time structural analysis provided crucial decision support, albeit only during the placement of the secondary laths. It would be interesting to examine how the initial form-finding could also be integrated in this process, as an alternative to the sequential ordering of design tasks.

Although initially assembled at the Ecobuild 2014 exhibition, due to its demountable and transportable design it is scheduled for future use by Ongreening Ltd. The structure follows a tradition of generating gridshells from timber, but in this case its geometry, demountability and assembly sequence suggests a unique approach to generating thin freeform shells.

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